# The Thermal Performance of Residential Electric Water Heaters Subjected to Various Off-Peak Schedules

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*An increasing number of utilities control the supply of power to residential water heaters as one means of reducing peak electrical demand. Water heaters operated in this manner are referred to as off-peak water heaters. Several utilities are also considering the use of solar domestic water heaters as an additional means of limiting power demand during times of greatest electrical usage. The research described within this paper quantifies the variation in thermal efficiency attributable to subjecting residential electrical water heaters to various off-peak and water removal schedules and, thus, forms a basis of comparison to which the thermal efficiency of solar water heaters or other water heating technologies may be compared. Laboratory tests, where the off-peak period and hot water draw schedule were varied, were conducted on two residential storage water heaters. A computer model of an electric water heater was developed and validated. The laboratory tests and the model were used to quantify the effect that various off-peak and hot water draw schedules have on water heater thermal efficiency. Thermal efficiency was found to vary up to seven percent for water heaters which meet the present minimum efficiency standards as specified within the National Appliance Energy Conservation Act. The energy factor, as measured using the Department of Energy Test Procedure for Water Heaters, is shown to be independent of the off-peak schedule because of a "normalizing" that occurs as part of the calculation procedure.*

## Introduction

In order to postpone the building of additional power plants, electric utilities are pursuing ways to limit peak power demand. Several utilities are presently using or are considering using solar water heating systems as a means for reducing peak demand. Interrupting the power input to the water heater, however, remains the leading method for reducing the demand caused by residential hot water needs. Electric water heaters operated in this manner are typically classified as off-peak water heaters.

Although the reduction in power demand is the key element when discussing off-peak water heaters, determining how off-peak operation affects water heater thermal efficiency is also of interest. Thermal efficiency depends on the standby losses from the tank, the amount of energy removed during hot water draws, and the recovery efficiency of the water heater.

A study was conducted at the National Institute of Standards and Technology (NIST) to document the variation in thermal efficiency and operating costs of conventional electric water heaters when subjected to various "off-peak" schedules. The results of this study form a basis to which the performance of solar domestic hot water systems for off-peak applications can be compared.

As part of this study, two storage water heaters were tested in NIST's Water Heater Laboratory (Fanney, 1990). Tests lasting 24 hours were conducted during which the water heaters were subjected to various off-peak and hot water draw schedules.

A computer program was written to model the transient response of an electric water heater during such 24-hour tests. After validating the model using the experimental data, the computer model was used to evaluate the thermal efficiency of an off-peak water heater which meets the Department of Energy (DOE) minimum efficiency standards (Federal Register, 1990).

In addition to reporting thermal efficiencies, energy factors are also reported. Energy factors are thermal efficiencies that are normalized according to the DOE Water Heater Test Procedure (Federal Register, 1990). A short discussion is given to explain why the energy factor of an electric water heater does not depend on the off-peak schedule.

## Background

The use of water heaters to manage electrical load is not a recent innovation. Detroit Edison, for example, first used water heaters as a load management tool in 1934 (Hastings, 1980). Utility-sponsored programs to limit and delay the operation of electric water heaters during peak demand periods continue because the demand reduction can be substantial. On a per water heater basis, Reed et al. (1989) reported 0.39 to 1.36 kW winter peak demand reductions and 0.22 kW to 1.2 kW summer peak demand reductions. Other load surveys have shown that the diversified demand of a typical electric water heater is approximately 1 kW during intervals when utilities are experiencing peak demand conditions (Hastings, 1980; Jack, 1976; Evaluation Subgroup, 1982; Abdoo et al., 1982). Thus, a utility with 100,000 electric water heaters under control could reduce its peak load up to 100 megawatts.

Electric utilities have used a number of techniques for controlling the load imposed by an electric storage water heater. The utility may directly control the power input to the water heater or attempt to limit the electrical demand imposed by water heaters through voluntary (incentive-type) controls. One example of voluntary control is when the utility informs the

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consumer that it is experiencing a peak load condition, and consequently, energy consumed during this time interval will be more expensive than energy consumed during off-peak conditions. A second method is to actively control when power is supplied to the water heater. For this second method, the two most common control strategies are cycling and payback (Evaluation Subgroup, 1982). For the cycling approach, power to groups of water heaters is disconnected for short time intervals whereas for the payback control strategy, power is disconnected for extended time intervals.

Unlike residential space-conditioning equipment, the electrical load imposed by a water heater on a utility is relatively constant throughout the year. An advantage to controlling electric water heaters, as opposed to other residential loads, is that the utility energy payback—the ratio of the energy consumed by the appliance if controlled to the energy which would have been consumed if the appliance was not controlled—is typically two to three times greater than the payback associated with air conditioners (Davis et al., Part II and Part III 1983). Based on payback tests where the supply power was interrupted from 30 minutes to eight hours in duration, American Electric Power (Evaluation Subgroup, 1982) concluded that only 18 percent and 28 percent of the utility's revenue would be lost in the winter and summer seasons, respectively.

Active control of the power input to water heaters is accomplished through the use of clock-actuated switches, and relays that respond to utility-generated carrier frequency signals or radio waves. Clock actuated switches have been used to disconnect the entire water heater or only the lower element (Akridge and Keebaugh, 1990). The use of clock-activated switches, although relatively inexpensive, results in a few disadvantages. The use of clocks results in a lack of flexibility because the "on-off" schedule remains fixed until the clock is reset. One study (Laaspere and Converse, 1975) estimates that approximately 0.5 man-hours per residence is required to reset a clock actuated timer, resulting in a huge cost to the utility if the peak load characteristics change with time. Another disadvantage associated with this method of control is that utility revenue is lost because no demand side load management is required during a significant number of days throughout the year. A study by Orange and Rockland Utilities (Nannery and Foltin, 1985) found that load conditions existed which warranted control of the water heaters only 32 hours during an entire year, less than 0.4 percent of the time.

The use of a carrier frequency on the distribution line, sometimes referred to as "ripple control," has been successfully used by many utilities. Although more expensive to implement than clock-actuated timers, carrier frequency control offers the utility flexibility in controlling the electrical demand while minimizing lost revenue. A third means to controlling water heaters is through the use of radio control, where a central transmitter broadcasts to receivers located at each residence. This approach offers additional flexibility over carrier frequency control because a number of transmitters and receivers operating at various frequencies can be utilized, thus allowing the utility to disconnect only a portion of the total water heaters under their control at any given time. Other techniques for controlling loads, including techniques where telephone and television cable services are used, have been considered but not implemented.

Although numerous studies have explored the use of electric water heaters for limiting the electrical demand on a utility, no studies were identified which quantify the thermal efficiency variations associated with demand-limiting controls on water heaters. This paper addresses this issue through a series of experiments on two electric storage water heaters and the use of a computer simulation model.

## Experimental Apparatus

A laboratory devoted to the evaluation and testing of water heaters (Fanney, 1990) was used to evaluate the effect of various off-peak modes of operation on the energy factor and the measured thermal efficiency of two electric water heaters. A commercially available 0.303 $m^3$ (80 gal) water heater with an integral microprocessor control unit was selected as one test specimen. This water heater is insulated with approximately 6.4 centimeters (2.5 in.) of foam between the storage tank and outer metal jacket. Water enters the tank through a horizontal diffuser located at the bottom of the storage tank. The heated water leaves the tank through a heat trap located within the foam

## Nomenclature

$A_c$ = cross-sectional area of water heater, $m^2$ ($ft^2$)
$A_i$ = surface area of water heater segment $i$, $m^2$ ($ft^2$)
$A$ = total surface area of water heater tank, $m^2$ ($ft^2$)
$C_p$ = specific heat, kJ/kg·°C (Btu/lbm·°F)
$E_f$ = energy factor of water heater, dimensionless
$H_l$ = history-dependent control logic variable for lower heating element, dimensionless
$J_i$ = heating element control function for node $i$, dimensionless
$J_l$ = heating element control function for the lower resistive thermostat, dimensionless
$J_u$ = heating element control function for the upper resistive thermostat, dimensionless
$k$ = thermal conductivity of water, W/m·°C (Btu/hr·ft·°F)
$\dot{m}$ = mass flow rate, kg/s (lbm/hr)
$N$ = number of nodes used to partition the water heater, dimensionless
$\dot{Q}$ = power supplied to heating element, W (Btu/hr)
$Q_{hw}$ = energy extracted from the water heater, MJ (Btu)
$Q_{in}$ = total electrical energy consumption, MJ (Btu)
$Q_l$ = total standby losses from the water heater, MJ (Btu)
$Q_{st}$ = change in stored energy within the water heater, MJ (Btu)
$t_a$ = ambient temperature, °C (°F)
$t_i$ = temperature of storage tank segment $i$, °C (°F)
$t_i^n$ = predicted future temperature of storage tank segment $i$, °C (°F)
$t_{l,\mathrm{off}}$ = setpoint temperature for lower resistive element thermostat, °C (°F)
$t_{l,\mathrm{on}}$ = temperature when the lower resistive element begins heating, °C (°F)
$t_m$ = temperature of the make-up water entering the water heater during a draw, °C (°F)
$t_{u,\mathrm{off}}$ = setpoint temperature for upper resistive element thermostat, °C (°F)
$t_{u,\mathrm{on}}$ = temperature when the upper resistive element begins heating, °C (°F)
$\Delta y_i$ = height of storage tank element $i$, m (ft)
$UA$ = heat loss coefficient-area product for the water heater, W/°C (Btu/hr·°F)
$UA_i$ = heat loss coefficient-area product for storage tank element $i$, W/°C (Btu/hr·°F)
$V$ = volume of storage tank, $m^3$ (gal)
$V_i$ = volume of storage tank element $i$, $m^3$ (gal)
$\eta_r$ = recovery efficiency of the electric water heater, dimensionless
$\eta_{th}$ = thermal efficiency of the water heater, dimensionless
$\rho$ = water density, $kg/m^3$ ($lbm/ft^3$)
$\tau$ = elapsed time, hr
$\Delta\tau$ = time step, hr

WATER HEATER OPERATION SCHEDULES

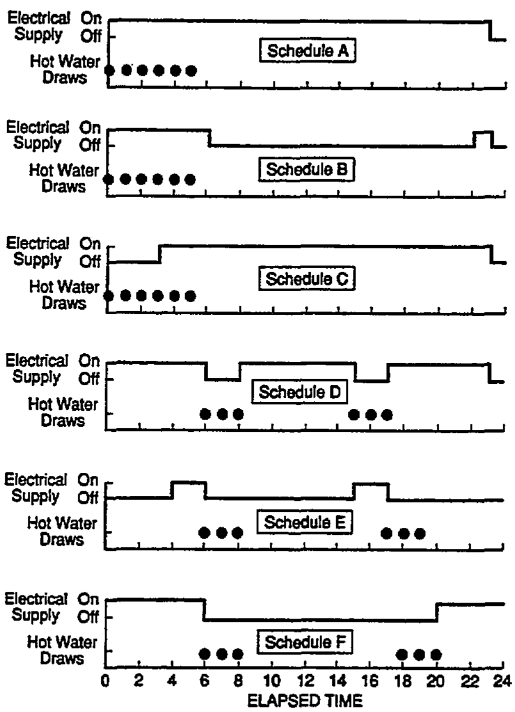


Fig. 1

insulation. Two interlocked 4500-watt resistive elements heat the water within the storage tank. The microprocessor, which controls the operation of the heating elements, is programmed using a personal computer and software supplied with the water heater. Using the software, a year can be divided into four segments with up to three "on" and "off" time intervals within a 24-hour period. In the remaining text, this first test specimen is referred to as the "insulated" water heater.

The second water heater tested consisted of a nominal 0.303 m$^3$ (80 gal) tank with *no* insulation or exterior jacket. An uninsulated tank was selected in an attempt to quantify the maximum benefit achievable through the use of an off-peak schedule. Water enters this tank through a vertical diffuser and exits through a port at the top of the storage tank. This water heater also incorporates two interlocked 4500-watt heating elements. A small pad of fiberglass insulation, approximately 15 by 20 centimeters (six by eight inches), was placed over each thermostat to promote proper operation. In the remaining text, this second test specimen is referred to as the "uninsulated" water heater.

## Experimental Results

A series of laboratory tests was conducted to determine the variation in energy factor and thermal efficiency due to different off-peak and water draw schedules. For Schedules A through D, Fig. 1, a 24-hour test was repeated two to three times on both the insulated or uninsulated water heaters. Two tests using Schedule E were conducted on the uninsulated water heater. Schedule F was used only in the computer modeling study. During each lab test the water heater thermostats were set to 57.2 ± 2.8°C (135 ± 5°F), and 0.243 m$^3$ (64.3 gal) of water were removed from the water heater as a result of six equal draws.

The six schedules, Fig. 1, differ in the manner in which water is withdrawn from the water heater and the hours during which electrical power is provided. Schedule A depicts the simulated use schedule and heating element operation specified within the DOE test procedure (Federal Register, 1990). Schedules B and C use the same water removal schedule as A but differ in the time periods in which electrical power is provided to the water heaters. Schedules D, E, and F represent water removal schedules in which the hot water draws are more representative of actual hot water usage in households which are unoccupied during the workday (Perlman and Mills, 1985). These last three schedules also vary in the times during which power is supplied to the water heaters.

The thermal efficiency and energy factor were calculated from the results of each laboratory test. Thermal efficiency, $\eta_{th}$, was calculated as follows:

$$\eta_{th} = \frac{Q_{hw}}{Q_{in} + \dfrac{Q_{st}}{\eta_r}} \tag{1}$$

where

- $Q_{hw}$ represents the quantity of energy removed from the water heater, MJ (Btu),
- $Q_{in}$ is the total electrical energy consumption, MJ (Btu),
- $Q_{st}$ is the change in the water heater's stored energy (initial–final), MJ (Btu), and
- $\eta_r$ equals 0.98, the recovery efficiency assumed for electric water heaters. The value of 0.98 asumes that two percent of the electrical energy supplied to the heating elements is not delivered to the water within the tank but lost to the surrounding ambient at the interface between the storage tank and heating element (Federal Register 1990).

The $Q_{in}$ term in Eq. (1) may be expanded such that thermal efficiency is expressed as

$$\eta_{th} = \frac{Q_{hw}}{\left[\dfrac{Q_{hw} + Q_l + Q_{st}}{\eta_r}\right]} \tag{2}$$

where $Q_l$ represents the total heat loss to the ambient, MJ (Btu).

Energy factor is defined the same as thermal efficiency except that the quantities $Q_{hw}$ and $Q_l$ in Eq. (2) are adjusted to a nominal set of test conditions account for variations in actual test conditions from nominal values (Federal Register, 1990). The adjustments permit comparisons of energy factors determined from different tests of the same water heater or from tests of different water heaters. Table 1 repeats the nominal test conditions and permissible test condition ranges specified within the DOE water heater test procedure.

As shown in Tables 2 the repeatability of the laboratory test results for each off-peak schedule was very good. For the insulated water heater, Table 2, energy factors and thermal efficiencies varied 0.013 or less. With the exception of test numbers 9 and 10 in Table 3, a repeatability level of 0.011 or less was observed for the uninsulated water heater. The 0.05 higher thermal efficiency for test 9 is attributed to lower tank standby losses. Lower standby losses occurred because the average ambient temperature was 24.85°C (76.7°F) for test 9 while for all other tests the air temperature was maintained at 21.60 ± 0.15 °C (70.9°F ± 0.3°F). The energy factors for tests 9 and 10 do not show the same variability, and 3, but rather differ by only 0.001. This close agreement reflects the impact of the mathematical adjustments made when calculating energy factor.

The off-peak and draw schedules did not affect the energy factor of the two water heaters but did significantly influence the thermal efficiency of the uninsulated water heater. The energy factors for both water heaters vary less than ± 0.01 from their respective average values, 0.865 for the insulated and 0.342 for the uninsulated. These variations are less than the estimated experimental uncertainty associated with determining an energy factor, ± 0.015. The thermal efficiency values for the insulated

Table 1 Rate conditions for residential water heaters

| Condition | Nominal Value | Allowable Range |
|---|---|---|
| Ambient Temperature | 19.7°C (67.5°F) | 18.3°C - 21.1°C (65.0°F - 70.0°F) |
| Average Tank Temperature | 57.2°C (135.0°F) | 54.4°C - 60°C (130.0°F - 140.0°F) |
| Supply Water Temperature | 14.4°C (58.0°F) | 13.3°C - 15.6°C (56.0°F - 60.0°F) |
| Water Withdrawn During Test | .243 m³ (64.3 gal) | 0.240 - 0.247 m³ (63.3 - 65.3 gal) |

water heater vary only ± 0.011 from the 0.882 average. The thermal efficiencies for the uninsulated water heater, by comparison, range from 0.346 to 0.513, or from 0.346 to 0.463 if test number nine with its higher ambient temperature is excluded. These differences in efficiency, 0.167 and 0.117, greatly exceed the difference that may be caused by experimental error (0.030). Thus, the thermal efficiency of the uninsulated water heater, is significantly affected by the off-peak and draw schedule imposed upon it.

An explanation for the variation in thermal efficiency is as follows. During on-peak intervals, the temperature of the water in the storage tank decreases, eventually to a point where resistive heating would occur if power was reconnected. From the time this normal recovery "point" occurs until power is reconnected, the thermal losses from the water heater are lower than the losses that would occur if power was not interrupted. Moreover, if constant volume draws are imposed when lower

Table 2 Summary of measured energy factors and efficiencies for the insulated water heater

| Test No. | Operation Schedule | Efficiency | | DOE Energy Factor | |
|---|---|---|---|---|---|
| | | Measured | Average | Measured | Average |
| 1 | A | 0.871 | 0.876 | 0.861 | 0.866 |
| 2 | A | 0.882 | | 0.871 | |
| 3 | A | 0.874 | | 0.866 | |
| 4 | B | 0.874 | 0.880 | 0.862 | 0.867 |
| 5 | B | 0.881 | | 0.867 | |
| 6 | B | 0.885 | | 0.872 | |
| 7 | C | 0.892 | 0.883 | 0.871 | 0.865 |
| 8 | C | 0.879 | | 0.859 | |
| 9 | C | 0.879 | | 0.861 | |
| 10 | D | 0.893 | 0.891 | 0.865 | 0.863 |
| 11 | D | 0.889 | | 0.861 | |
| Overall Average | | 0.882 | | 0.865 | |

Table 3 Summary of measured energy factors and efficiencies for uninsulated water heater

| Test No. | Operation Schedule | Efficiency | | DOE Energy Factor | |
|---|---|---|---|---|---|
| | | Measured | Average | Measured | Average |
| 1 | A | 0.365 | 0.367 | .336 | .339 |
| 2 | A | 0.368 | | .342 | |
| 3 | B | 0.459 | 0.460 | .346 | .347 |
| 4 | B | 0.460 | | .348 | |
| 5 | C | 0.357 | 0.352 | 0.345 | 0.342 |
| 6 | C | 0.346 | | 0.338 | |
| 7 | D | 0.365 | 0.365 | 0.340 | 0.340 |
| 8 | D | 0.364 | | 0.339 | |
| 9 | E | 0.513 | 0.488 | 0.342 | 0.346 |
| 10 | E | 0.463 | | 0.341 | |
| Overall Average | | 0.406 | | 0.342 | |

than normal top tank temperatures exist because of on-peak operation, the energy removed is reduced. The quantities $Q_l$ and $Q_{hw}$ in Eq. (2) both decrease, thus changing thermal efficiency. By comparison, the DOE procedure used to calculate the energy factor adjusts the actual thermal losses from the water heater to the quantity which would have occurred if the average temperature difference between the water heater and ambient air had been 37.5°C (57.2°C − 19.7°C [135°F − 67.5°F]). The DOE procedure also adjusts the energy removed during each draw so that the energy factor is based on an average water heater outlet to inlet temperature difference of 42.8°C (57.2°C − 14.4°C [135°F − 58°F]). In both cases, the adjustment is made by multiplying the experimental energy quantity, thermal losses or energy removed during draws, by the ratio of the nominal temperature difference (37.5°C [67.5°F] or 42.8°C [77.0°F]) to the measured temperature difference.

The experimental results show that for a well-insulated water heater the influence of the off-peak schedule on thermal efficiency is less than the overall experimental uncertainty. For an uninsulated water heater, however, the off-peak schedule can have a significant impact on the thermal efficiency of the water heater. Thus, the remaining issue is to determine the magnitude to which the thermal efficiency varies as a function of the off-peak and draw schedule for an electric storage water heater that has an energy factor which meets the requirements of the National Appliance Energy Conservation Act (NAECA). NAECA requires that electric storage water heaters sold after Apr. 15, 1991 have energy factors equal to or greater than

$$E_f = 0.93 - 0.34871 * V \quad (3)$$

where $V$ is the nominal volume of the water heater, m³. Water heaters which have energy factors less than the value from Eq. (3) need not be considered since they cannot be sold.

## Computer Modeling Effort

Rather than attempt to locate and test water heaters which exactly meet the NAECA requirements, a computer program that simulates the operation of an electric storage water heater was developed, validated, and subsequently used to determine the variations in thermal efficiency attributable to various off-peak and hot water draw schedules. The computer model is based on a one-dimensional heat transfer analysis outlined by Duffie and Beckman (1980) which ignores heat transfer due to conduction. The tank is divided vertically into $N$ elements. An energy balance on the $i$th element yields the following differential equation:

$$(\rho C_p V)_i\,(t_i^n - t_i) = (\dot{m}C_p)_i\,\Delta\tau\,(t_{i+1} - t_i) - UA_i(t_i - t_a)\,\Delta\tau + J_i\dot{Q}\Delta\tau. \quad (4)$$

The left-hand side of Eq. (4) represents the increase in the internal energy of the element. The first term on the right-hand side represents energy transport caused by a draw. The remaining two terms on the right-hand side account for, respectively, the heat loss to the surroundings and the external energy added to the element by resistive heating.

For nodes which have a heating element, the control function $J_i$, is used to emulate the same control scheme used by an actual water heater, including the interlocking feature which prevents both elements of a two-element tank from heating at the same time while giving priority to the upper element. For the upper heating element of a two-element tank, the heating element control function, $J_u$, is defined as

$$J_u = \begin{cases} 1 & \text{if } t_i \le t_{u,\text{on}} \\ 0 & \text{if } t_i \ge t_{u,\text{off}} \\ J_u^p & \text{if } t_{u,\text{on}} < t_i < t_{u,\text{off}} \end{cases} \quad (5)$$

where $t_{u,\text{on}}$ and $t_{u,\text{off}}$ are the "turn-on" and "turn-off" temperatures of the upper thermostat, and $J_u^p$ is the control function determined for the previous time step. The control function for the lower heating element, $J_l$, is defined as

$$J_l = \begin{cases} 0 & \text{if } J_u = 1 \\ 1 & \text{if } J_u = 0 \text{ and } H_l = 1 \end{cases} \quad (6)$$

where

$$H_l = \begin{cases} 1 & \text{if } t_i \le t_{l,\text{on}} \\ 0 & \text{if } t_i \ge t_{l,\text{off}} \\ H_l^p & \text{if } t_{l,\text{on}} < t_i < t_{l,\text{off}} \end{cases} \quad (7)$$

Similar to Eq. (5), the variables $t_{l,\text{on}}$ and $t_{l,\text{off}}$ are the turn-on and turn-off temperatures of the lower thermostat, and $H_l^p$ is the $H_l$ value from the previous time step. The control function $J_i$ is zero for all nodes not having a heating element.

During a draw, make-up water is assumed to displace water from the node having a temperature closest to but less than the entering make-up water, or the bottom node if the temperature of the make-up water is lower than the bottom node temperature. For the typical case where the make-up water does enter the bottom node—as was the case for all simulations conducted in this study—the characteristic equation becomes

$$(\rho C_p V)_b\,(t_b^n - t_b) = (\dot{m}C_p)_b\,\Delta\tau\,(t_m - t_b) - UA_b\,(t_b - t_a)\,\Delta\tau + J_b\dot{Q}\,\Delta\tau \quad (8)$$

where the subscript $b$ designates the bottom tank node. At the beginning of each time step, the ON/OFF status of the draw and the resistive elements ($J_l$ and $J_u$) are determined. The temperature of each node, $t_i^n$, is calculated by solving Eq. (4) using the explicit Euler method. The new node temperatures are compared to determine if the temperature of each node is less than or

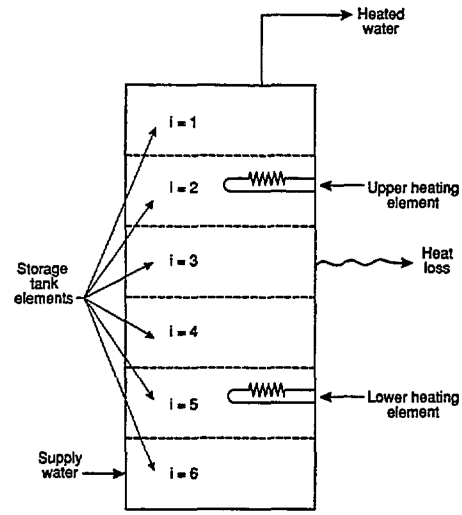


Fig. 2

equal to the temperature of those nodes positioned immediately higher in the tank. If a temperature inversion exists, the temperatures of the "hot" node and those nodes immediately above it having a lower temperature are averaged. Each node is then assigned this new average temperature. This final step accounts for the buoyancy-induced currents that defeat inverted stratification.

Although Duffie and Beckman (1980) state that three nodes are typically sufficient, the authors chose six because the laboratory experiments were conducted using six vertically spaced tank temperature sensors. A six node tank is illustrated in Fig. 2. The $UA$-value for each node was assigned as follows:

$$UA_i = \frac{A_i}{A}\,UA \quad (9)$$

where

- $A_i$ is the tank surface (i.e., outer metal jacket) area associated with each node, m$^2$ (ft$^2$),
- $A$ is the total surface area of the water heater, m$^2$ (ft$^2$), and
- $UA$ is the measured overall $UA$-value for the water heater, W/°C (Btu/hr°F).

The measured $UA$-value for the insulated and uninsulated water heaters are 1.89 W/°C (0.14 W/°C standard deviation) and 23.38 W/°C (0.20 W/°C standard deviation), respectively.

Based on physical measurements of the two tanks and experimental observations, the upper thermostat and resistive element were modeled as being located in the second node. Because the extent of heating that occurred in the very bottom of the water heaters varied, the lower resistive element was modeled as being in the bottom node for some simulations while being in the fifth node for others. For both cases, the thermostat for the lower element was modeled as sensing the tank temperature of the fifth node.

After evaluating the effect from using different time increments, a one-minute time step was used for all computer simulations.

**Validation of Model.** The computer model was validated by comparing predicted thermal efficiencies against the laboratory test results for the insulated and uninsulated water heaters. The input information supplied to the computer model in order to conduct each 24-hour simulation is summarized in Table 4. The temperatures associated with each node within the storage tank were set equivalent to the measured values at the beginning of each simulation. For selected days, the predicted thermal efficiencies are compared to the measured values in Table 5.

Table 4 Input data for water heater model validation

| Parameter | Insulated Water Heater | Uninsulated Water Heater |
|---|---|---|
| Tank Volume | 0.273 $m^3$ (72.0 gal) | 0.295 $m^3$ (78.0 gal) |
| Main Water Temperature | 14.4°C (58.0°F) | 14.4°C (58.0°F) |
| Surface Area | 3.53 $m^2$ (38.0 $ft^2$) | 2.59 $m^2$ (27.9 $ft^2$) |
| Overall Measured UA Value | 1.89 W/°C (3.58 Btu/hr°F) | 23.38 W/°C (44.32 Btu/hr°F) |
| Operation Schedule | A-D | A-E |
| Upper Element | | |
| Wattage | 4500 Watts | 4500 Watts |
| On-Temperature<br>Off-Temperature | Set According to Experimental Observation | Set According to Experimental Observation |
| Lower Element | | |
| Wattage | 4500 Watts | 4500 Watts |
| On-Temperature<br>Off-Temperature | Set According to Experimental Observation | Set According to Experimental Observation |

The model was capable of predicting the measured results to within five percent for both water heaters. The difference between measured and predicted results are partially attributed to assumptions within the model which ignores conduction, horizontal temperature gradients, and convection plumes which exist when the heating elements are energized. The predicted efficiencies varied from schedule to schedule in a manner consistent with the measured results. For the insulated water heater, for example, the simulation predicts the same highest to lowest ordering of thermal efficiency (Schedules D-C-B-A) as was experimentally determined. When comparing the effect of Schedule B versus C for the uninsulated water heater, the predicted change in thermal efficiency (0.098) is very close to the measured change (0.102).

**Parametric Studies.** Using the validated model, simulations were conducted to determine the influence of different operating schedules on the thermal efficiency of two water heaters which meet the NAECA standards. Fictitious water heaters having rated capacities of 0.310 $m^3$ (82 gal) and 0.454 $m^3$ (120 gal) were selected for the study and will be referred to hereafter as Tank A, and Tank B, respectively. Larger volume water heaters such as Tanks A and B would be preferred for a residential off-peak application, especially if the on-peak hot water demand is anticipated to be substantial.

Using the computer model to simulate the 24-hour test specified in the DOE test procedure (Federal Register, 1990), the overall $UA$-value was varied until the energy factors met the NAECA requirements. Given these $UA$-values, the simulation program was then used to examine the variation in thermal efficiency due to various off-peak and draw schedules. Simulations using equal volume draws of 0.0406 $m^3$ (10.717 gallons) and equal energy draws of 7.146 MJ (6775 Btu) were conducted. The simulations using draws based on energy were included to isolate the effect of standby losses.

For Tank A, predicted thermal efficiencies for operation schedules A through F are given in Table 6. The predicted thermal efficiencies vary from 0.821 to 0.878 or 6.8 percent for simulations using equal volume draws. Similarly, thermal efficiency varies from 0.818 to 0.876 or 6.9 percent for simulations using equal energy draws. The greatest variation in the predicted thermal efficiencies for Tank B, given in Table 7, was 6.6 percent for both equal volume and equal energy draws. The agreement between the two draw scenarios occurs even though the energy removed for the equal volume draws, $Q_{hw}$, varies from 38.407 MJ (36,412 Btu) to 43.990 MJ (41,705 Btu) for Tank A and from 41.331 MJ (39,184 Btu) to 43.982 MJ (41,697 Btu) for Tank B. For comparison, 42.876 MJ (40,649 Btu) were removed in all simulations where the draws were based on energy.

Notably, for tests where draws are based on volume, a higher thermal efficiency does not necessarily ensure lower electrical energy use. An indicator of day-in-day-out energy use, the denominator of Eq. (1), is listed in Table 8 along with its corresponding Tank A efficiency. The denominator, referred to as the total energy input in Table 8, does not vary from lowest to highest when the efficiencies are ordered from highest to lowest. In fact, the second lowest total energy input, 48.251 MJ (13.403 kWh), corresponds to the lowest thermal efficiency, 0.821. By comparison, a consistent inverse correlation occurs between efficiency and total energy input for cases where the same amount of energy is removed during the day. When draws are based on volume (which infers that the end use is temperature insensi-

Table 5 Validation of water heater model with measured performance data

| Test No. | Operation Schedule | Measured Thermal Efficiency | Predicted Thermal Efficiency | Percent Difference (%) $(\eta_p - \eta_m)/\eta_m$ |
|---|---|---|---|---|
| **Insulated Water Heater** | | | | |
| 1 | A | 0.871 | 0.857 | -1.6 |
| 4 | B | 0.874 | 0.858 | -1.8 |
| 7 | C | 0.892 | 0.863 | -3.3 |
| 10 | D | 0.893 | 0.864 | -3.3 |
| **Uninsulated Water Heater** | | | | |
| 2 | A | 0.368 | 0.379 | 2.9 |
| 3 | B | 0.459 | 0.460 | 0.2 |
| 5 | C | 0.357 | 0.362 | 1.4 |
| 8 | D | 0.364 | 0.382 | 5.0 |
| 9 | E | 0.513 | 0.535 | 4.3 |

Table 6 Water heater model simulation results for a 0.310 $m^3$ (82 gallon) electric storage water heater which meets NAECA minimum efficiency requirements

| Operation Schedule | Predicted Thermal Efficiency of Tank A | |
|---|---|---|
| | Simulations Using Constant Volume Hot Water Draws | Simulations Using Constant Energy Hot Water Draws |
| A | 0.822 | 0.818 |
| B | 0.822 | 0.819 |
| C | 0.821 | 0.829 |
| D | 0.825 | 0.829 |
| E | 0.878 | 0.876 |
| F | 0.854 | 0.867 |

tive), less energy may be removed, thus requiring less electrical energy to replace the withdrawn energy and a lower total energy input. This lower energy removal acts to reduce the numerator relative to the denominator of Eq. (2), thus causing thermal efficiency to decrease. When draws are based on energy (which infers the end use is 100 percent temperature sensitive), the same amount of electrical energy is needed to replace the withdrawn energy. The distinguishing variable is then how much electrical energy is needed to offset the standby losses. As losses increase, the total energy input increases and thermal efficiency decreases because only the denominator of Eq. (2) increases.

An estimate can be made, using the information in Tables 8 and 9, of the cost savings attributable to operating Tanks A and B as off-peak water heaters. The maximum savings for Tank A should range between 8.417 MJ/day (2.338 kWh/day) and 3.377 MJ/day (0.938 kWh/day), the higher number corresponding to a scenario where the temperature of the water does not alter the daily volume used. Assuming the cost of electricity is $0.022 per megajoule ($0.08 per kWh), these daily differences amount to a maximum annual cost savings between $68 and $27. For the larger Tank B, the maximum daily energy savings is predicted to range between 5.559 MJ/day (1.544 kWh/day) and 3.417 MJ/day (0.949 kWh/day), where again the greater savings corresponds to using the same volume of hot water each day regardless of its temperature. Thus, the

Table 7 Water heater model simulation results for a 0.454 $m^3$ (120 gallon) electric storage water heater which meets NAECA minimum efficiency requirements

| Operation Schedule | Predicted Thermal Efficiency of Tank B | |
|---|---|---|
| | Simulations Using Constant Volume Hot Water Draws | Simulations Using Constant Energy Hot Water Draws |
| A | 0.774 | 0.770 |
| B | 0.775 | 0.771 |
| C | 0.775 | 0.780 |
| D | 0.780 | 0.781 |
| E | 0.827 | 0.822 |
| F | 0.808 | 0.813 |

Table 8 Expanded comparison of simulation results for Tank A

| Simulations Using Constant Volume Hot Water Draws | | | Simulations Using Constant Energy Hot Water Draws | | |
|---|---|---|---|---|---|
| Operation Schedule | Thermal Efficiency | Total Energy Input (MJ) | Total Energy Input (MJ) | Thermal Efficiency | Operation Schedule |
| E | 0.878 | 48.686 | 47.995 | 0.876 | E |
| F | 0.854 | 44.060 | 48.452 | 0.867 | F |
| D | 0.825 | 50.418 | 50.677 | 0.829 | C |
| B | 0.822 | 52.434 | 50.706 | 0.829 | D |
| A | 0.822 | 52.477 | 51.336 | 0.819 | B |
| C | 0.821 | 48.251 | 51.372 | 0.818 | A |

projected maximum annual cost savings for Tank B is between $45 and $27. The operating cost variations and savings would be less than those reported in this study if the utility demand-side management program requires the water heater have an energy factor that exceeds the NAECA minimum efficiency standards.

## Conclusions and Recommendations

The control of electric storage water heaters is an effective means of residential load management. This paper, through the use of experimental data and computer simulations, has shown that thermal efficiency is affected by the manner in which the water heater is controlled. The results of this study form a basis to which the variation in thermal efficiency of other water heating technologies, when subjected to various off-peak and water removal schedules, may be compared. For water heaters that meet the minimum efficiency specified within the National Appliance Energy Conservation Act, the efficiency was found to vary by as much as seven percent. Assuming a constant thermal load, the annual operating cost for a 0.454 $m^3$ (120 gal) electric water heater could be reduced by approximately $27 through the use of an appropriate control strategy. The actual reduction in operating cost may be substantially more since some end uses of hot water are insensitive to the temperature of the water being delivered (e.g. dishwasher, clothes washer). Thus, the thermal load of a controlled water heater will be less than or equal to that of an uncontrolled unit.

Table 9 Expanded comparison of simulation results for Tank B

| Simulations Using Constant Volume Hot Water Draws | | | Simulations Using Constant Energy Hot Water Draws | | |
|---|---|---|---|---|---|
| Operation Schedule | Thermal Efficiency | Total Energy Input (MJ) | Total Energy Input (MJ) | Thermal Efficiency | Operation Schedule |
| E | 0.827 | 52.038 | 51.127 | 0.822 | E |
| F | 0.808 | 50.108 | 51.660 | 0.813 | F |
| D | 0.780 | 53.518 | 53.788 | 0.781 | D |
| B | 0.775 | 55.620 | 53.863 | 0.780 | C |
| C | 0.775 | 52.567 | 54.490 | 0.771 | B |
| A | 0.774 | 55.667 | 54.544 | 0.770 | A |

The energy factor is not affected by the way that the water heater is controlled. The calculation procedure used to compute energy factor adjusts the both the average storage tank temperature and the average outlet temperature during a draw to a nominal value of 57.2°C (135°F). Thus, any decrease in thermal losses that is achieved by disconnecting the electrical power for an extended period is not taken into account and any effect from delivering water at a temperature other than 57.2°C is negated.

The development of a DOE test procedure which addresses off-peak water heaters would be extremely difficult. The main difficulty would be the selection of a standard off-peak schedule. Numerous strategies are employed to use water heaters as a demand side management tool. For example, some water heaters are controlled in an identical manner each day through the use of clock-actuated timers. The on-peak and off-peak times are utility dependent and change as the utilities' load mix changes with time. More frequently, utilities use carrier frequency or radio control to disconnect water heaters only when needed. The current DOE test procedure gives the "worst-case" results since it assumes the water heater will be energized throughout the entire year. Since it is impossible to select a "typical" operation schedule, the authors feel that the current DOE procedure, which will yield conservative results, is the most appropriate technique for evaluating all electric storage water heaters.

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